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FINAL REPORT

on

LASER COOLING AND TRAPPING OF NEUTRAL ATOMS

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by

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The information in this report is approved for general distribution.

Table of Contents

Report on Research Accomplished under ONR Contract for the period 1 October 1989 to present (July 1992).

BACKGROUND

In 1988, before the beginning of the current contract period, our group discovered that sodium atoms could be laser cooled well below the lower limit (the "Doppler limit") predicted by the then generally accepted theory. Two main consequences of that discovery were a revamping of the theory of laser cooling and a renewed interest in the applications of laser cooling because of the far lower temperatures. Both of these effects are continuing in full force today, and this report is in large part a record of our group's continuing involvement in the new developments in laser cooling during the past three years. The work of the NIST laser cooling group falls functionally into the categories of: investigating laser cooling mechanisms; studies of collisions between laser cooled atoms; development of new trapping techniques for neutral atoms; study of the fluorescent spectrum of laser cooled atoms; manipulation of atoms and atom optics; development of coherent sources of vacuum ultraviolet light for laser cooling and high resolution spectroscopy; application of laser cooling and trapping technology to atomic frequency standards. The results of research in this area are summarized below and explained in detail in the following sections. The supplementary program in experimental and theoretical collision studies is also summarized below and then discussed in detail in separate sections.

SUMMARY OF RESEARCH RESULTS

Laser cooling mechanisms: The early theories advanced to explain laser cooling below the Doppler limit predicted certain functional dependences of the temperature on laser parameters of intensity and detuning. *In collaborative work with colleagues in* Paris we confirmed these dependences, and confirmed experimentally the newly emerging understanding that there was a threshold value for the laser parameters that allowed the new laser cooling mechanisms to work. Additional work at NIST was directed to quantitative comparisons with explicit three-dimensional calculations, investigating both the absolute temperature and the dependence of the temperature on the atomic structure. These results indicate that in spite of correct prediction of functional dependence, the theories are not correctly predicting the actual numbers obtained in experiments. We have also done new theoretical calculations of the cooling and forces on atoms in a magnetic field, a problem relevant to the magneto-optic trapping of atoms. Such trapping is the most popular form of atom trap at present, but its operation is not at all understood in detail

New traps for neutral atoms: In collaboration with Prof. I. Silvera at Harvard we have constructed a microwave trap for cesium atoms. The principle of this trap is that the energy of interaction between the atoms and a microwave field near resonant with the hyperfine transition varies in space, in a microwave cavity, so as to create a potential well. The experiment is close to being operational, and if successful will be pursued for application to trapping spin polarized hydrogen for Bose condensation. Another new trap is the Far Off Resonance Trap (FORT) which is simply a laser dipole-force trap operated so far off resonance that it neither heats nor seriously perturbs the energy levels of the atom. This idea has been made practical in part because of the extremely low temperatures achievable with sub-Doppler laser cooling. We have shown that such a trap can be operated cw, without the usual switching of the trap to avoid cooling inhibition.

Fluorescence Spectrum of laser cooled atoms: Just previous to the present contract period we had begun to investigate the

measurement of the spectrum of fluorescent light from atoms as a method for measuring the temperature of the atoms in situ. That was successful, but we also found that the atoms showed evidence of being trapped in the sub-wavelength sized optical potential wells created by the interference of the laser beams used in the cooling (optical molasses). During this contract period we have improved on the techniques for obtaining the spectrum, devising some new instruments for the purpose, and have extended the measurements to atoms trapped in one dimension. In this case the spectrum simplifies and shows clear evidence of the oscillatory nature of the motion of atoms trapped in the 1-D potentials as well as the quantized nature of that motion.

Atom Optics: This field refers to manipulating atoms or atom beams in ways analogous to the manipulation of light and light beams by ordinary optical elements such as lenses and mirrors. We have been developing curved mirrors for atoms. Already demonstrated as flat mirrors, these work by reflecting atoms from the dipole-force potential in an evanescent wave resulting from total internal reflection of light inside a dielectric. The evanescent wave extends into the vacuum, and reflects sufficiently slow atoms before they contact the surface. We have demonstrated this on a curved surface for the first time and have seen two bounces of the atoms.

Atomic Fountain Clocks: One of the most fortunate results of the laser cooling of atoms below the Doppler cooling limit is that the use of neutral atom atomic fountains for atomic clocks becomes much more realistic than previously. The atomic fountain clock is an old idea, dating back to Zacharias in the mid 1950's. Atoms are launched vertically through a microwave cavity, falling back through again under the influence of gravity. The two passages in the cavity constitute a Ramsey separated oscillatory field interaction, as in a conventional atomic clock, but with a much longer interaction time. The ultracold atoms now possible allow the interaction time to be on the order of a second without so much transverse spreading that most of the falling atoms do not return through the cavity. In collaboration with our colleagues in Paris we have demonstrated the resonance for such a clock and shown that its potential performance, even for a preliminary experiment, equals the best present day cesium clocks. We have analyzed a new prospective optical frequency standard that will use the same fountain technology.

Vacuum Ultraviolet generation: We have developed the techniques for generating coherent VUV at the Ly-α wavelength for cooling and manipulating hydrogen or anti-hydrogen. The same techniques can also be used for high resolution spectroscopy of He, to test QED in a two-electron system. We have demonstrated extremely high efficiency for the generation and have partly developed the high resolution frequency sources.

Collisions of laser cooled atoms: During the previous contract period we had studied associative ionization of laser cooled and optically trapped sodium atoms, confirming qualitatively a theoretical prediction of Julienne that the rate of this process should depend dramatically on laser intensity. Since then both the theory and the experiment have been refined, with quantitative measurements of the ratio of reaction rates at high and low laser intensity, and measurements of the spectrum of ionization as a function trap laser detuning. These data are compared to new theoretical calculations and provide some evidence for previously unobserved molecular levels.

Supplementary collisions program, Theory: (This program is led by Paul Julienne of the NIST Molecular Physics division.) Collisions occurring between atoms cooled to laser cooling temperatures have properties very different from collisions at ordinary temperatures. For example, at more usual collision energies, radiative lifetimes are generally long compared to collision times, so little spontaneous emission occurs during a collision. For cold collisions, this situation is reversed, requiring different theoretical methods to treat the collision process. An understanding of the collisions is not only intrinsically interesting but also essential for understanding loss mechanisms for losses from traps, shifts in atomic clocks, and the evolution of quantum collective behavior in dense systems.

Supplementary collisions program, Experiment: (This program is led by John Weiner, Dept of Chemistry, University of Maryland.) Studies of ultra cold collisions in traps can probe the lowest energy interactions of atoms but are less adapted to measuring the energy dependence of collisions and collision properties that depend on the collision axis relative to the atomic polarization. Atomic beam experiments allow such measurements.

We have performed atomic beam collision experiments using advanced velocity selection techniques to obtain collision energies between 1000 K and 18 mK.

Detailed reports on each of the research areas follow.

LASER COOLING MECHANISMS

As originally conceived in 1975 [1,2] and expounded in detail in 1979, laser cooling results from the velocity dependence of the radiation force on near resonant atoms. The velocity dependence arises from the Doppler shift of the apparent resonant frequency, and so this laser cooling is generally called Doppler cooling. When the laser is tuned below the atomic resonance, increased absorption by atoms moving opposite to the laser propagation leads to a damping force. This is accompanied by a heating effect due to the random nature of absorption and emission. The balance between damping or cooling and heating leads to a temperature which can be no lower than $k_B T = \hbar\Gamma/2$, where Γ is the linewidth of the resonance. This temperature is known as the Doppler cooling limit, and is 240 μK for sodium cooled on its resonance line. In 1988 [4] we measured laser cooling temperatures in optical molasses [5,6], an arrangement of counterpropagating laser beams, and found temperatures much lower than the Doppler limit. Eventually we measured sodium temperatures as low as 25 μK, about an order of magnitude below the Doppler limit.

The sub-Doppler cooling was explained as arising from the multilevel nature of the atoms, optical pumping among the atomic levels, and light shifts of the levels [7,8]. One of the major thrusts of our work during this contract period has been the testing of the theory of sub-Doppler cooling and of more sophisticated theories that followed. A simplified discussion of the theory is given in ref. [9].

Some of our early experiments testing the theory of sub-Doppler cooling were accomplished by the time of the previous report in 1989, and the complete record of these tests is in ref. [6]. One important prediction was that the temperature of the atoms should depend linearly on I/δ, the intensity divided by the detuning of the laser (in the limit of low intensity and large detuning). Our measurements indeed showed that the temperature depended linearly on the intensity, but as seen in Fig. 1 below, the dependence on detuning was not in particularly good agreement with the prediction.

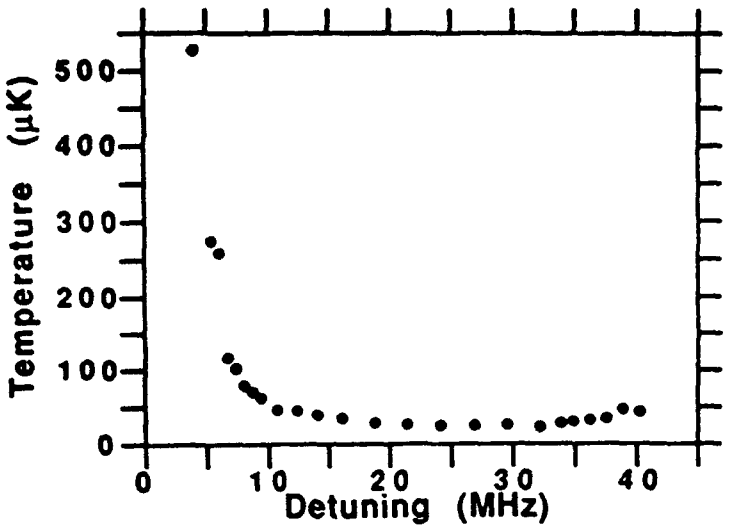

Fig. 1: Temperature of Na atoms laser cooled in a 3-D optical molasses as a function of laser detuning, from ref [6].

The likely explanation for the behavior departing from $1/\delta$ in Fig. 1, and particularly the increase in temperature at large δ is that in Na the detuning could not be made very large before the laser started to come close to resonance with another hyperfine level. Simply stated, one couldn't get into the large detuning limit without making the problem far more complicated by the addition of another energy level. This problem may be solved by using cesium, where the analogous additional level is much further away. The experiments with cesium are described below.

Another important observation described in ref. [6] is the existence of a threshold for the intensity at which the new cooling mechanism would work. We established experimentally that if the laser intensity were below a critical value the temperature increased dramatically. This was expected on the basis of the theory presented in [7], but the understanding of this phenomenon (now known as *décrochage* or disintegration of the molasses) was still imperfect at the time of those experiments. The 1-D theory predicted that the new cooling mechanism provided a large damping force only for velocities smaller than some critical velocity

dependent on intensity and detuning. Beyond that velocity, the damping is less effective, and at larger velocity only Doppler cooling operates. The point of view, expressed in [6] was that once the critical velocity (dependent on intensity) became smaller than the width of the velocity distribution, the cooling would break down.

While the experiments confirmed the idea of a threshold intensity at which the cooling ceased, more quantitative measurements, and a closer look at the theory presented a different picture.

In collaboration with colleagues at Ecole Normale Supérieure in Paris, we studied the behavior of laser cooled cesium in optical molasses [10]. As expected, we confirmed the dependence of the temperature on I/δ for this case where a large detuning could be cleanly obtained. Fig. 2 shows that for a wide range of parameters the temperature depends only on I/δ, and for most of the range, the dependence is linear. Only at small detuning or large intensity, where the theory is expected to break down, is there a deviation from linearity.

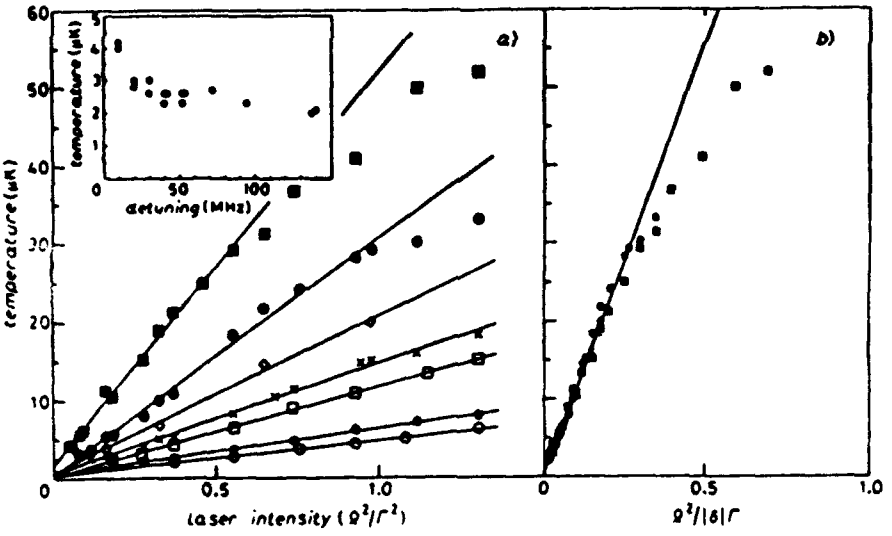

Fig. 2: Temperature of Cs atoms laser cooled in 3-D optical molasses (from ref. [10]). In (a) temperature is plotted as a function of intensity; in (b) it is plotted as a function of I/δ.

The availability of a large parameter space allowed us to study how the threshold intensity varied with detuning. The result was

that, except for the smallest detunings, The threshold occurred at a constant value of I/δ. This finding was at odds with the original image of décrochage, but consistent with the new viewpoint, based on the understanding that as the atomic velocity exceeds the critical velocity, leading to reduced damping, it also leads to reduced heating, with the result that the extent of the velocity distribution can greatly exceed the critical velocity while the cooling continues to work well. Thus, the threshold intensity can be much lower than previously supposed, and the temperature also lower. In fact, the lowest temperature is found to be roughly independent of the choice of intensity or detuning, since the threshold occurs at constant I/δ, the single parameter determining temperature.

For cesium, this lowest temperature was found to be only 2.5 ± 0.6 μK [10], a value which was at the time the lowest temperature ever measured in 3-D for any substance. The velocity corresponding to this temperature for Cs is about 1 cm/s, or about three times the recoil velocity, the velocity change experience by an atom on emitting or absorbing a single photon. Interestingly, the lowest temperature measured for sodium in our laboratory [6] also corresponded to about three recoil velocities. All this was consistent with the theoretical understanding that the lowest temperature should depend on the recoil velocity.

For the Cs temperature measurements the uncertainty was very much reduced from the typical ±10 μK in our early Na measurements. As in the early measurements, the temperature was determined from the time-of-flight distribution of atoms released from optical molasses. The main reason for the improvement was that for the heavier Cs atoms the time-of-flight distribution is simpler than for the lighter Na, and the spatial distribution of atoms was "sliced" so as to reduce geometric uncertainties before the atoms were released for the TOF measurement.

The agreement between these experiments and the theory, satisfying as it was, was still only qualitative. The dependence on the parameters was as predicted, but the theory was for only one dimension, and for a simpler set of energy levels than possessed by the atoms used in our 3-D experiments. I fact, the numerical results for the 3-D measurements in Cs gave temperatures close to three times higher than the predictions for the same laser parameters and

a simpler level structure. It is tempting to ascribe the factor of three to the fact that three times as much total light intensity falls on the atoms in the 3-D experiment. Nevertheless, no direct comparison with theory or a clear expectation of such a scaling law existed. In order to make more quantitative comparisons, we have done both three dimensional calculations and one dimensional experiments. The one dimensional experiments are described in the section on fluorescence spectra.

In collaboration with a colleague at the University of Aarhus in Denmark, we have calculated the temperature of atoms of various degrees of level degeneracy in a three dimensional situation. The method of calculation [11] lacks the sophistication of the most advanced 1-D theories available in that it is semiclassical and makes the approximation of low velocity. Nevertheless, these same approximations are known to be good ones in the 1-D case, and it is, in any event, the only available 3-D calculation.

The experiments to compare with this theory have been done in our laboratory at NIST, using the apparatus which was under construction at the beginning of this contract period. The atom chosen for these measurements is rubidium. Rb has two abundant isotopes, in contrast to Na and Cs, which have only one. The entire sub-Doppler cooling mechanism depends on the existence of a manifold of normally degenerate ground states. The different nuclear angular momenta of the two isotopes ^{85}Rb and ^{87}Rb lead to different degeneracy, and therefore, presumably, different cooling characteristics. The results of the temperature measurements for two isotopes of Rb are shown in Fig. 3 below.

According to the theory, the ratio of the slopes of the lines showing temperature vs. light shift should be 0.69, where ^{85}Rb, with the higher angular momentum, has the lower temperature. In fact, we find that the ratio of the slopes is about 0.90 ± 0.05, where ^{85}Rb has the lower temperature. Thus, the simple theory gives a very wrong result for the ratio of slopes, a number that is quite insensitive to systematic errors because everything else about the atoms and the measurement is virtually identical except the angular momentum and a small mass difference. It is particularly surprising that the temperatures should be so close to being equal. Also, the absolute slope is similar to the absolute slope measured for both Cs and Na, although an accurate comparison is difficult because of the uncertainties about calibration that are absent from the isotope

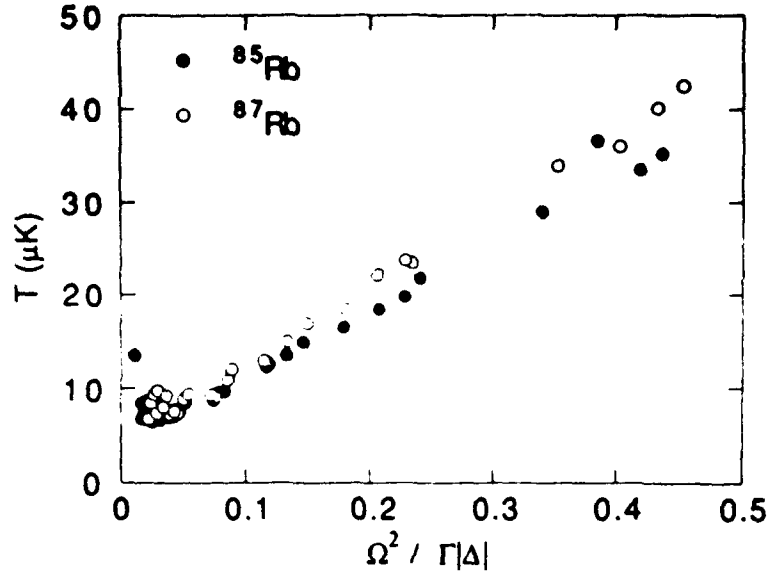

Fig. 3: Temperature of Rb atoms in 3-D molasses as a function of laser intensity and detuning, for two isotopes [ref. 12].

comparison. Nevertheless, there appears to be a tendency for universality in the temperature of laser cooled atoms that is unexpected. This matter is still under investigation and a publication on the isotope comparisons is being prepared.

In an attempt to improve our understanding of magneto optic trapping, we have made a detailed theoretical study of laser cooling in a $\sigma^+ - \sigma^-$ configuration, that is, counterpropagating laser beams with opposite circular polarizations. It is this configuration in 3-D, along with a quadrupolar magnetic field, that forms the magneto optic trap. This work was done in collaboration with Jean Dalibard who was a visitor with our group for eight months.

In contrast to previous treatments of this problem, we do not make the assumption that ground and excited states have the same g-factor [7], nor do we adiabatically eliminate the excited state [13]. We do, however use a semiclassical treatment. Using the simpler assumptions, it had been found that the addition of a magnetic field was completely equivalent to a change in velocity of the atom. That is, the force on an atom depended only on the sum of the Doppler shift and the Zeeman shift. Using the more correct assumptions we find this not to be the case. In particular, because the Doppler cooling is sensitive to the excited state g-factor and the sub-Doppler cooling is sensitive to the ground state g-factor, the

situation is not so simple and we find that, for example, at sufficiently high fields (several gauss for typical laser parameters) the sub-Doppler cooling is effectively eliminated. The force vs. velocity for several magnetic fields is shown in Fig. 4. below. When the field is sufficient that the high slope portion of the curve does not intersect zero velocity, sub-Doppler cooling is ineffective. We are planning experiments to test these 1-D calculations. We have also studied theoretically the prospect of magnetically launching atoms. That is, application of a small enough magnetic field simply induces a drift velocity to the cold atoms. This can be used in an atomic fountain (see below) to launch the atoms up in the fountain. The problem with the g-factors limits how much of a launch is possible, but we predict that it could be of some utility. The details of all these calculations are described in a forthcoming publication [14].

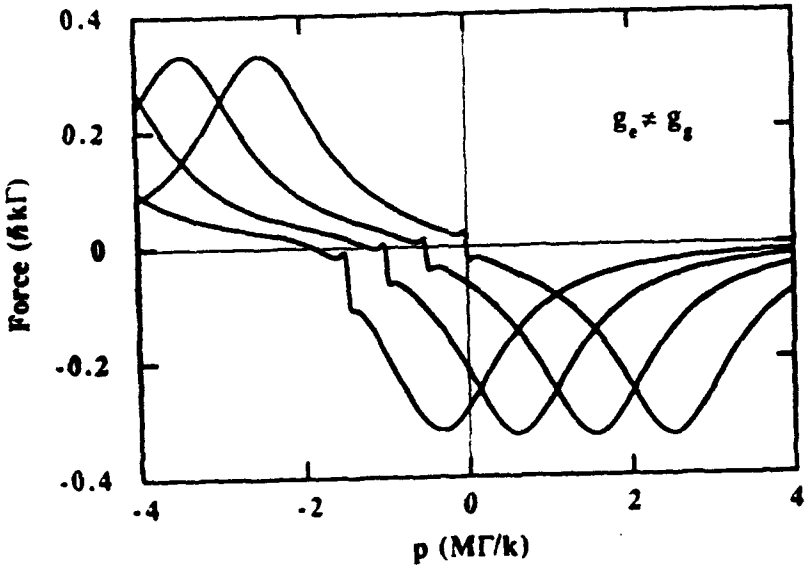

Fig. 4: Force vs. velocity in the σ^+- σ^- configuration with longitudinal fields from zero to 1.2 mT. Sub-Doppler cooling is ineffective by 0.8 mT.

A final aspect of fundamental studies of laser cooling mechanisms involves the spatial diffusion of atoms undergoing laser cooling. This spatially diffusive motion was one of the key characteristics predicted for optical molasses even before sub-Doppler cooling was discovered [5]. It is manifested by the fact that atoms in an optical molasses are confined for a significant time even though there is no restoring force. This viscous confinement

results from the long time for the atoms to diffuse out of the molasses. Experimentally, diffusion times on the order of one second are observed for a one centimeter diameter molasses. This is consistent with estimates made in the absence of sub-Doppler cooling [6] and is considerably shorter than a naive calculation based on sub-Doppler cooling. In fact, it has been known, but not published, from work in our own group and the group at Ecole Normale Supérieure in Paris, that the behavior of the diffusion time was not consistent with truly diffusive motion. In particular, the time to diffuse out of a certain size molasses did not depend as the square of the diameter of the molasses, but as something closer to linear in the diameter.

We decided to study both the theory and experiment more closely. With Jean Dalibard, we calculated spatial diffusion constants using the semiclassical form of the sub-Doppler laser cooling force combined with the Doppler cooling force. For experimental measurements, done with Rb atoms, we did not simply measure the escape of atoms from an optical molasses by observing the decay of the molasses after it is loaded. This traditional method suffers from the fact that any other mechanism for losing atoms, such as scattering by background gases, contributes to the loss.

Instead, we started with a magneto optic trap, made by using the appropriately circularly polarized laser beams and the appropriate magnetic field, to capture atoms at fairly high density in a small (mm-sized) volume. Then the magnetic field was turned off, and the polarization of the light, the intensity and detuning were switched to the desired values. The light polarization was electronically switched using a fast liquid crystal polarization switch. All of this switching takes place in a few milliseconds, so the atoms hardly diffuse at all. After that, we recorded the spatial evolution of the atom cloud using a video camera and a video recorder. The recorded video images were digitized and analyzed. By examining the growth of the atom cloud in the molasses, we have a direct measure of the diffusion.

The initial trials showed that there was a substantial drift along with the diffusion. In fact, the drift was so fast compared to the diffusion that it was dominating the escape of the atoms from the molasses. One reason for such a drift is that the counterpropagating beams of the molasses are achieved through retroreflection. Losses on windows and mirrors create an intensity

imbalance leading to drift. To correct this we used six independently adjustable beams, and found that the drift could be effectively eliminated. Also, with higher quality coatings we found that the drift with retroreflected beams could be reduced to a manageable level.

With the drift under control, we were able to plot the square of the spatial extent of the atom cloud as a function of time. For diffusive motion, this should yield a straight line. In fact, we found that for a variety of methods of analysis, all the methods gave a linear evolution and agreed well for the slope, at least for times shorter than about two seconds. Typical data is shown in fig. 5. For longer times the signal becomes small and is difficult to analyze. In any case, the motion is seen to be diffusive, with diffusion constants as small as 10^{-3} cm^2/s. The dependence of the diffusion coefficient on detuning and intensity is found to be qualitatively similar to that predicted by the 1-D theory, but not of the correct magnitude. This may be understandable considering the difference in dimensionality and the fact that the 1-D calculation was done for a different transition scheme than Rb. Nevertheless, the qualitative feature of the theory, that the diffusion minimizes for a finite detuning, is reproduced in the data. The dependence on detuning is shown in fig. 6. The data for the diffusion measurements is still being analyzed and we expect to be able to submit it for publication in the Fall of 1992.

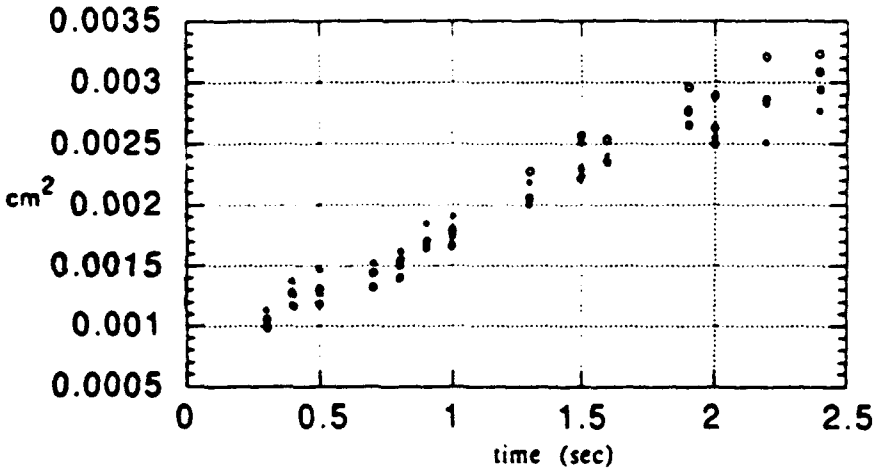

Fig. 5: Spatial extent of the Rb atom cloud as a function of time as it expands into an optical molasses. The different symbols are for different analysis methods.

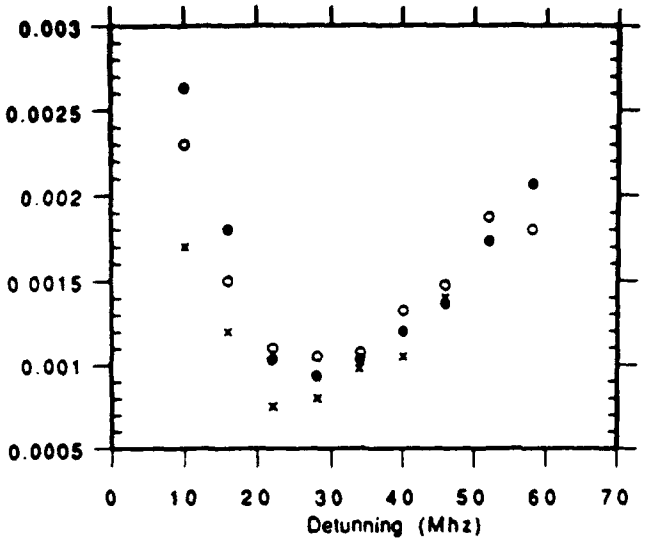

Fig. 6: Measured spatial diffusion constant in Rb as a function of laser detuning.

Diffusion coefficients as small as 10^{-3} cm^2/s imply that atoms live for about 100 s in a spherical molasses with boundaries at 1 cm radius [6]. In fact, such long times are never seen, although we did see a mean lifetime longer than 12 s in a 9 mm radius molasses. The actual lifetime in our experiments is limited by collisions with background gases, and we suspect that in many cases where molasses lifetimes were measured the lifetimes were dominated by drift, as was the case for us before great care was taken to balance the beams. Furthermore, any non-uniformity of the laser beams could create local imbalance that would look very much like diffusion. We sometimes observed that after long times, with well balanced beams, the atoms would drift in different directions in different parts of the molasses. All of this indicates that the general failure to see long molasses lifetimes is not because the diffusion constant is too large, but because there are other factors, which may mimic diffusion, that limit the lifetime.

NEW TRAPS FOR NEUTRAL ATOMS

One of the applications for trapping of neutral atoms is to the search for Bose condensation of a cold atomic gas. Bose condensation is a condensation in momentum space, producing, in the idealized case, a macroscopic fraction of the population in the lowest energy state of the trap when the temperature and density of the gas are such that the deBroglie wavelength is on the order of the interparticle spacing. While something akin to Bose condensation evidently occurs in liquid He at the superfluid transition, that system is a dense liquid with many strong interactions between the atoms. The goal discussed here is to see the phenomenon in a weakly interacting gas.

The search for BEC has centered on spin polarized atomic hydrogen because it does not form molecules, nor condense even at absolute zero. One problem has been that it sticks to the walls of a container at very low temperature, allowing spin flips and molecule formation. Magnetic trapping eliminates the walls, but a static magnetic trap can only hold the magnetic sublevels whose energy increases with increasing field. This means that in any finite field, the opposite direction of the spin has lower energy and collisions can lead to a spin flip by an exothermic reaction. Such flipped spins are expelled from the trap. A dynamic, or oscillating magnetic field can trap either direction of the spin, but the oscillating field, typically oscillating at an audio frequency, must be fairly large. It has generally been thought that the eddy currents likely to be induced by such an oscillating field would be incompatible with the cryogenic environment of a spin polarized hydrogen sample.

Recently, Silvera and colleagues [15] proposed a different sort of trap, based on the same principle used in laser dipole traps, but using radio frequency fields. Briefly, the trap works because the spatially varying rf field in a microwave cavity leads to a spatially varying potential energy of interaction between the field and the atom having a spin resonance near the rf frequency. The interaction Hamiltonian mixes the two spin states, producing two new (dressed) eigenstates having opposite energy shifts. In the absence of relaxation either dressed state can be occupied, although only one is trapped, depending on whether the tuning of the rf is above or below resonance. An appropriate choice of detuning can make the trap hold atoms which are predominantly of one spin state or the other, and thus the trap can be made to hold the most stable of the spin states.

Such a trap has not yet been demonstrated, but should make it possible to trap a larger density than has been possible with static magnetic traps, where the density is limited by the spin flipping collisions.

We have, in collaboration with Silvera's group at Harvard, constructed a microwave cavity having the required inhomogeneity and resonant frequency to trap cesium atoms using the hyperfine transition at 9.2 GHz. This is to be used as a test of principle before constructing a trap for hydrogen. To the microwave trapping field we have added a gradient magnetic field to compensate for the gravitational potential. Cesium is so heavy that the microwave potential is not sufficient to hold an atom up against gravity. With hydrogen, there should be no such problem. The gradient will be arranged in such a way that by itself it does not constitute a trap, but merely cancels the effect of gravity.

The experiment will work as follows: Cesium atoms will be cooled and trapped in a magneto optic trap using laser beams passing through optical access holes in the microwave cavity. Once the magneto-optic trap is turned off, the atoms should be held by the microwave field. As the magnetic field of the magneto-optic trap is turned off, the anti-gravity field will be turned on. Success of the trapping process will be assessed by recapturing the atoms in a magneto-optic trap and observing the fluorescence.

The status of the experiment is that the cavity is undergoing final tests and the apparatus used for the studies of laser cooling in Rb has been converted to Cs. Trapping and cooling of Cs atoms to temperatures as low as 2.5 μK has been confirmed. The depth of the microwave trap is a several tens of microkelvins, depending on the amount of microwave power delivered to the cavity. We expect to be trying the trapping experiment shortly.

Another new prospect for trapping atoms is the Far Off Resonance Trap (FORT). This is a variation of the laser dipole trap already in use in our laboratory for collision studies (see below). As already noted, the operation of this kind of trap is similar to the rf trap described above. The laser polarizes the atoms and the induced oscillating dipole moment interacts with the spatially varying laser field to create a trapping potential. Because of relaxation from spontaneous emission the most populated dressed level is always

the one which is predominantly ground state. This leads to trapping at a maximum of the laser field for detuning below resonance.

The dipole trap has so far [16,17] been used only in an alternated mode. That is, the trap is switched on and off, with periods of trapping alternated with periods of laser cooling in optical molasses. There are two reasons for this. First the trapping field causes heating that needs to be counteracted by repeated cooling. Second, the trap induces a strong light shift (the trapping potential) that makes the cooling inoperative by introducing a substantial inhomogeneous change in the effective detuning. Thus, the cooling is only effective when the trap is off.

The idea of the FORT is that the trapping laser is tuned so far from resonance that the light shift is small enough not to interfere with cooling. Ultimately the trap is far enough off resonance that it produces little heating, so that cooling is hardly needed [18]. The thing that makes such a possibility realistic is the new cooling mechanisms producing sub-Doppler cooling. First, the improved cooling produces such low temperatures that the trap does not have to be very deep. Second, good cooling with the sub-Doppler mechanism is accomplished with large detuning from resonance. This means that the small light shift of the trapping potential does not much disturb the cooling.

Using sub-Doppler cooled sodium atoms we have succeeded in demonstrating the operation of a FORT under conditions that do not require alternated operation. The trap is a single laser beam, tightly focussed so as to produce an strong maximum of intensity at the focus. By tuning the trap about 5 nm red of resonance, the trap was effective in holding the atoms without having to turn it off to allow cooling by the molasses which was always present [19]. These results represent only a preliminary demonstration. We expect to use even larger detunings so that atoms may be held for several seconds without any cooling from molasses.

In connection with these experiments we have observed another interesting phenomenon. When the trapping laser is not very strongly focussed, we observe trapping of atoms at a number of points along the axis of the trapping laser. These points do not move along this axis as the focus is moved, but do move with the trapping laser as it moves transverse to the axis of the beam. Instead the multiple points appear to be tied to a structure fixed in the cooling

molasses. Apparently there is a dipole force caused by an interference in the molasses that is sufficient to pin atoms at various points along the axis of the "trapping" laser. We have not yet identified the exact mechanism for this additional pinning force, but it is related to interference between the multiple laser beams forming the 3-D molasses, but with a spatial periodicity much greater than an optical wavelength. We suppose that it has to do with misalignments between the laser beams, but we have not fully investigated the phenomenon. Ultimately, for a strongly focussed trapping laser, we do not expect the molasses trapping effect to be dominant. Furthermore, it should be minimized when the trap is tuned far enough off resonance that less cooling is needed. For these reasons, we do not expect the molasses pinning effect to cause difficulties, but we do expect to understand the origin of the effect.

FLUORESCENCE SPECTRUM OF LASER COOLED ATOMS

At the end of the previous contract period we reported that we had just made the first observations of the spectrum of the fluorescence of Na atoms being cooling in a 3-D optical molasses. The techniques used involves mixing the fluorescent light and light derived from the molasses laser on a photodiode. The beat signal contains all the spectral information about the fluorescence without the fluctuations of the laser. An example of the type of spectrum seen after we had made sufficient improvements in the S/N is shown in fig. 7.

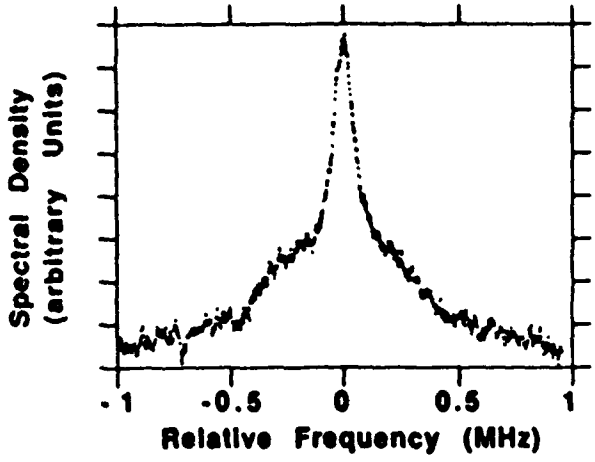

Fig. 7: Spectrum of fluorescence of laser cooled Na atoms.

The spectrum shows a broad pedestal that reflects the Doppler width of the cold atoms. In this case the temperature deduced from the Doppler width was fairly high, about 80 μK, since a high laser intensity was used to get a good signal. This temperature agreed with a measurement using the time-of-flight method. The narrow feature on top of the pedestal represents atoms trapping in the sub-wavelength sized potential wells formed by the interference of the laser beams making up the molasses. The narrowing is due to the Dicke effect, whereby Doppler broadening is suppressed when an atom is confined to a region much smaller than a wavelength. We also studied the behavior of the broad and narrow peaks as a function of laser intensity and detuning and compared these measurements with some simplified models. These results are described in ref. [20].

The spectrum of Fig. 7 was obtained using a conventional rf spectrum analyzer to analyze the beat signal from the photodiode.

While this works quite well, it has the disadvantage of being a single channel technique in which only a single frequency element of the spectrum is obtained at a time, while the information about other frequency elements is wasted. In order to make more efficient use of the small signal, we developed a parallel processing spectrum analyzer. The principle of this analyzer is that the rf signal to be analyzed is used to drive an acousto-optic modulator (AOM). Within appropriate limits the AOM deflects light (from an alignment laser, for example) by an angle proportional to the frequency applied and with an intensity proportional to the power applied. In this way, the distribution of deflected light represents the rf spectrum. The instrument made in this way exceeded the resolution capabilities of any commercial device and three of our group members received an RD100 award from Research and Development magazine for its design.

The new instrument allowed us to obtain more spectra more quickly, and to see features not easily seen with the conventional spectrum analyzer. For example, we were able to see an even broader pedestal which is the central component of the so-called Mollow triplet. This feature has a width on the order of the natural line width (10 MHz in Na) and is difficult to see compared to the much narrower central part of the spectrum just because it is so wide and has low spectral density. The spectrum in Fig. 7 is often called the "elastic" part of the fluorescence spectrum and in previous measurements of fluorescence has not been fully resolved. By contrast, our measurements resolve the substructure of this component and see the wider components only with difficulty. Therefore, these measurements are complementary to the measurements made of the Mollow triplet at much lower resolution. More details of these later measurements are found in ref. [21].

One of the puzzles about a spectrum such as Fig. 7 is that while the atoms are trapped, there is no evidence in the spectrum of the oscillation of atoms in the potential wells. If the atoms were oscillating, that should, in a classical picture, lead to phase modulation sidebands, or in a quantum picture, sidebands at the oscillation frequency due to transitions between bound levels of the potential well. We never saw such sidebands, and we attributed that to the fact that they were broadened by relaxation mechanisms that did not broaden the central sharp feature. Very briefly, we expected the sidebands to be broadened by the rate at which photons were absorbed (lifetime of the ground state) but the central feature to be

broadened only by the inverse of the residence time in a potential well. Calculations [22, 23] showed that for an atom like Rb or Cs it should be easier to see the sidebands. The laser could be detuned far enough from resonance that the atoms would oscillate many times in the potential well before absorbing and spontaneously emitting a photon, a situation that should lead to resolved sidebands. The fact that the laser would be substantially detuned meant that it was important to use a parallel processing spectrum analyzer to get good S/N. Unfortunately, the AOM based spectrum analyzer had at best 30 kHz resolution, which was insufficient for a spectrum as narrow as expected from Rb. The problem with Rb, compared to Na, is that the temperature would be lower, because the recoil energy is smaller (see the section on cooling mechanisms above). Furthermore, the heavier mass would lead to a smaller velocity for the same temperature, and the longer wavelength would give a smaller Doppler shift for the same velocity.

In order to overcome these difficulties, we designed still another type of spectrum analyzer, this time a real time, averaging fast Fourier transform analyzer. This analyzer used a digital signal processing board dedicated to the data acquisition and transforming, producing a device with both large bandwidth and high duty factor. Various combinations of parameters could be used, but a typical choice was a resolution of 4 kHz, a frequency span of 500 kHz, and a 25% duty factor.

In order to simplify the interpretation of the spectral data, we made the experiment one-dimensional as follows: Rubidium atoms were trapped and cooled in a magneto-optic trap, then further cooled in 3-D optical molasses, the 3-D molasses was switched off, and a 1-D molasses, consisting of counterpropagating beams with orthogonal linear polarization was switched on. After this 1-D molasses had equilibrated the atoms, we observed the fluorescence, beat it on a photodiode with the reference laser and Fourier analyzed it with our FFT analyzer. The fluorescence was observed at a very small angle from the 1-D axis in order to minimize the effects of uncooled transverse motion on the spectrum.

A typical spectrum is shown in Fig. 8. The spectrum is interpreted as follows: The polarization configuration used creates periodic potential wells for atoms in a given magnetic sublevel. These potential wells have a number of bound states. The central feature results from transitions beginning on a given bound

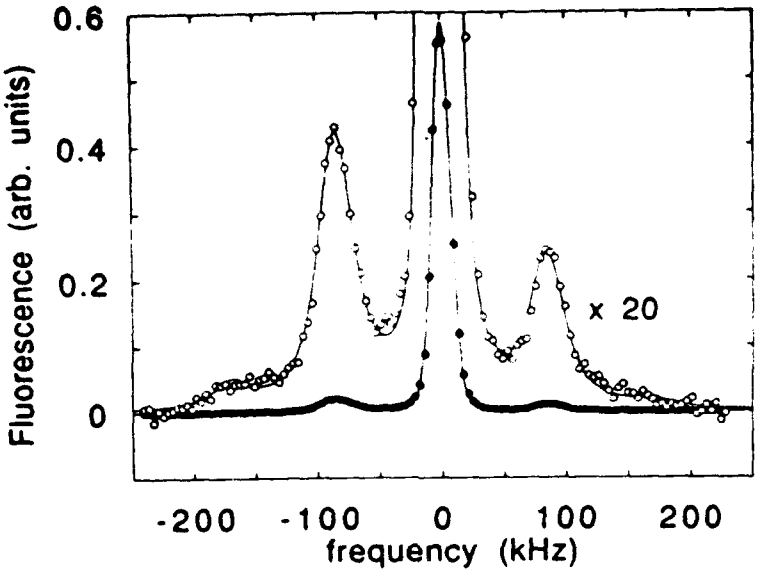

Fig. 8: Spectrum of fluorescence from Rb atoms laser cooled in a 1-D optical molasses with orthogonal linear polarizations in the counterpropagating beams. (From ref. [24].)

vibrational level with the absorption of a photon and the subsequent emission of a fluorescent photon upon return to the same bound level. Because the state of the atom does not change, the frequency shift of the fluorescent photon, compared to the absorbed laser photon, is zero. The sidebands result from transitions that end on higher or lower vibrational levels than the original level, and so are higher or lower in frequency by the vibrational level spacing.

The asymmetry in the sideband height results from the non-uniform distribution of population among the various bound levels of the wells. Since the lowest levels are most populated, transitions from lower to higher vibrational levels are most common, so the lower frequency sideband is strongest. The degree of asymmetry gives us a measure of the temperature, assuming a Boltzmann distribution among the levels. If we plot the temperature obtained in this way as a function of light shift (as is done in Fig. 2 for 3-D cooling) we find a straight line, just as in the 3-D experiments. The temperature is about a factor of 3 smaller than the 3-D temperatures measured for Rb, as described in the section on cooling mechanisms. At present we do not have calculations of the temperature for Rb in 1-D with orthogonal linear polarizations, but

such calculations are doable and will be compared with the experiments.

The spectra give information about the vibration frequency of atoms in the potential wells. This vibrational frequency should vary as the square root of the light shift, because the stiffness (spring constant) of the potential well restoring force varies as the depth of the potential, which is the light shift, and the oscillation frequency goes as the square root of the stiffness. Fig. 9 shows the

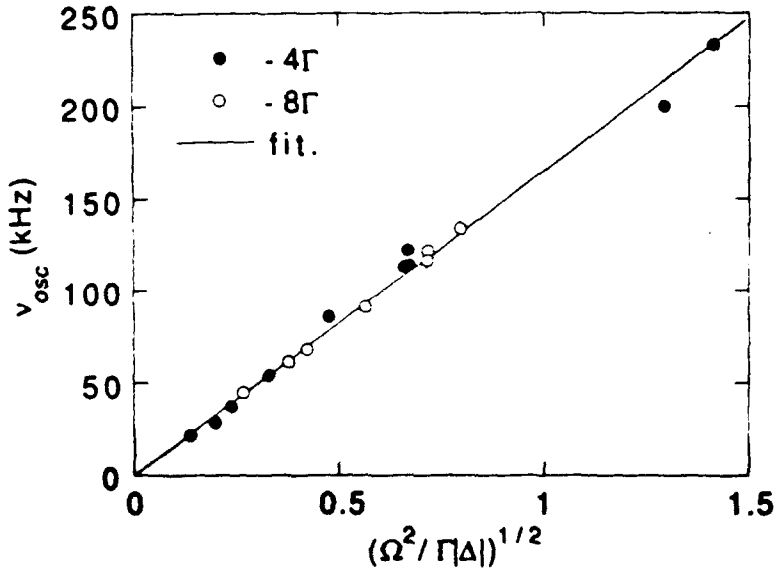

Fig. 9: Sideband spacing (vibrational frequency) as a function of the square root of the light shift. (From ref. [24].)

measured sideband spacing as a function of $\Lambda^{1/2}$, where $\Lambda = \Omega^2/\Delta\Gamma$, where Ω is the Rabi frequency, Δ the detuning and Γ the linewidth. Λ is proportional to the light shift, and as expected, the oscillation frequency varies linearly as the root of Λ. The observed slope agrees with the calculated oscillation frequency, including the effect of anharmonicity, to better than 10%. The difference is only marginally significant, but might be due to neglect of the effect of damping and saturation in the calculation.

The smallness of the sidebands in Fig. 8 provide a measure of the confinement of the atoms in the potential wells. Classically, the sidebands are small because they result from phase modulation

with small modulation index. Quantum mechanically, they are small because transitions in which the vibrational quantum number changes are suppressed more strongly for low-lying vibrational levels. We find that the rms spread of the atomic position distribution is only 1/15 of an optical wavelength for most values of the laser parameters. For the lowest temperatures (smallest light shifts), this implies that 60% of the population is in the ground vibrational state.

The highly quantum mechanical nature of this system suggests that it should be possible to manipulate the bound atoms so as to produce coherent states of oscillation or even to produce squeezed states of oscillatory motion.

ATOM OPTICS

Atom optics is the manipulation of atoms or atomic beams in ways analogous to the way light is manipulated by optical elements such as lenses and mirrors. A few such analogs have been demonstrated. One dimensional lenses using radiation pressure forces have been used to focus and image atomic beams. Flat mirrors using evanescent light waves have been used to reflect atoms or atomic beams. Our work in this area has been to make a curved mirror for atoms, with a view to its use for focussing or storing atoms.

An evanescent wave atomic mirror [25] is based on the action of the dipole force. Light, totally internally reflected from a dielectric-vacuum interface, extends into the vacuum with exponentially decreasing intensity. The resulting gradient of intensity produces the force that can reflect atoms of sufficiently small velocity. Such a plane mirror has been demonstrated for glancing reflection of a thermal atomic beam [26] and normal reflection of cold atoms dropped from a trap [27].

In the absence of spontaneous emission, the reflection of atoms from the evanescent wave is elastic and specular, just as in the reflection of light from a mirror. The requirement for reflection is that the kinetic energy of the atom normal to the mirror surface be smaller than the dipole potential at the surface. In this way, the atom never makes contact with the substrate surface, an occurrence which would normally lead to inelastic processes. If the surface of the mirror is curved, it can be used to focus or confine the atoms. In particular, atoms dropped from above a curved mirror surface can be trapped by the dipole potential on the mirror and the gravitational field. This sort of "gravito-optical trap" has been studied in detail, including the quantum mechanical modes atoms can occupy in the trap. Because of the wave nature of the atoms, the trap or "gravity cavity" behaves in a way analogous to a Fabry-Perot etalon, supporting certain distinct quantum modes. Even for very cold atoms, however, the typical mode is of very high order, with many modes of the cavity being occupied.

One difficulty in making a curved evanescent wave mirror is that light must reflect from a curved interior surface, resulting in a reflected beam with large divergence. This presents the practical difficulty of disposing of the reflected beam without allowing a

significant amount of light to illuminate the region above the mirror where the atom will bounce. By using a monolithic design incorporating a prism and a concave lens, we have minimized the stray light problem.

Another difficulty is in avoiding spontaneous emission during the time the atoms are bouncing. This is achieved by tuning the laser far from resonance, which causes the rate of spontaneous emission to decrease more rapidly than the dipole force. Since the gradient in the evanescent wave is very strong, the wave having a characteristic decay length on the order of $\lambda/2\pi$, the time for bouncing is short and the probability of spontaneous emission is low. We calculate that an atom should bounce about 10 times from a height on the order of a centimeter using an evanescent wave produced by a few hundred milliwatts of laser power. Since the time spent bouncing is short, on the order of a microsecond, and the time between bounces is long, on the order of 100 milliseconds, the intensity of the light above the mirror must be five orders of magnitude smaller than the intensity on the mirror to have a similar rate of inducing spontaneous emission. Hence the great concern for reducing stray light from the laser.

Very recently we have reported the successful bouncing sodium atoms from a curved mirror with a radius on the order of 2 cm [28]. We have observed two bounces. This is insufficient to see the trapping effect of the curvature, but we expect to extend the number of bounces so as to see this effect.

ATOMIC FOUNTAIN CLOCK

The idea of an atomic fountain was first proposed by Zacharias in the 1950's. He envisaged sending an atomic beam of cesium atoms up through a microwave cavity tuned to the hyperfine frequency, and allowing them to fall again through the same cavity, executing a Ramsey separated oscillatory fields resonance. The long interaction time would give a narrow resonance feature, while the double passage through the cavity would cancel certain systematic errors. Realization of a fountain had to wait for the development of laser cooling, and in fact, it was not until sub-Doppler cooling was demonstrated that the first fountain was made [29]. The difficulty encountered by Zacharias was that in a thermal atomic beam there are essentially no atoms going slowly enough that, after being directed upward, they would fall back within a reasonable distance. Laser cooling certainly provided such atoms, but the problem remained that even at the lowest temperatures achievable with Doppler cooling, the transverse thermal velocities of the atoms was so great that after any reasonable fountain round trip time, the atoms would have spread out so much that very few would make it back through the microwave cavity.

As an example, consider Na atoms cooled to the Doppler cooling limit. The rms velocity along a given axis would be 30 cm/s a the Doppler temperature of 240 μK. If the fountain were a meter high, the round trip time would be about a second, and the atoms would spread out to cover an area greater than 3000 cm^2 by the time they returned to the starting point. By contrast, cesium atoms, laser cooled by the sub-Doppler cooling mechanism to 2.5 μK, have an rms velocity of about 1 cm/s, and so would spread to an area three orders of magnitude smaller. Under such conditions a substantial fraction of all the launched atoms could return through a hole in a microwave cavity.

The first demonstrated fountain [29] used Na atoms launched into a section of waveguide where the microwaves were pulsed twice to produce the Ramsey resonance. This produced a narrow line because of the long parabolic trajectory in the large waveguide, but it did not realize the idea of Zacharias to pass twice through a cavity, a process that tends to cancel systematic errors due to variations in the microwave field across the cavity. In addition, the method of launching the atoms was to push them vertically using a

single laser beam. The disadvantage of this method is that the atoms heat in both the vertical and transverse directions due to the random nature of photon absorption and emission.

Our experiment, performed in Paris, used a different launch mechanism, a modification of the moving molasses proposed in ref. [6]. In this moving molasses the frequency of the two laser beams in the vertical arms is shifted compared to that of the horizontal arms. The descending beam is shifted down and the ascending beam is shifted up. An atom moving up with the appropriate velocity sees these beams Doppler shifted to the same frequency as the horizontal beams. This is the configuration the atoms perceives as being a static molasses and it cools to a low temperature in this moving frame. The result is atoms moving with a uniform vertical velocity at as low a temperature as can be obtained in stationary molasses.

The experiment, described in ref. [30], involved first collecting Cs atoms in an optical molasses, then sweeping the frequency of the appropriate beams so as to accelerate the atoms into a moving molasses, then equilibrating at a low temperature in the moving molasses before turning off the molasses beams allowing the atoms to be launched. The atoms were optically pumped into a given hyperfine state, and the change of state was detected by selective optical excitation after the Ramsey resonance. The experimental set up is shown in fig. 10.

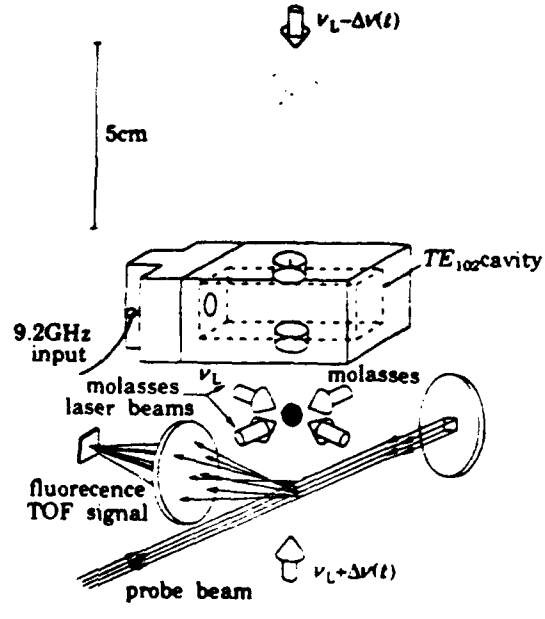

Fig. 10: Apparatus for the Cs fountain Ramsey resonance experiment.

The resonance signal, which shows the usual Ramsey interference pattern is given in Fig. 11. Each point corresponds to several launches and detections at a given frequency driving the microwave cavity. A significant source of noise is the variation in the number of atoms launched at any given time. This effect is minimized by a normalization technique where after the second passage through the atoms making the hyperfine transition are detected for part of the detection period and the total number of atoms launched is detected during another part. The signal corresponding to the atoms making the transition is normalized to the total number of atoms to reduce the noise.

Another source of noise is the instability in the frequency source used to generate the microwave signal. If this latter source of noise is eliminated (which would be the case for a high quality crystal oscillator being used as the reference for generating the microwaves) then the short term, noise limited performance of a clock operated using this device would be 3×10^{-12} in one second. This is as good as the performance of any laboratory standard cesium clock currently in operation.

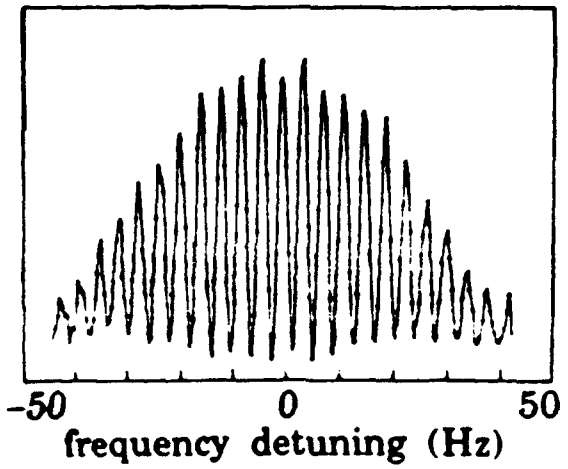

Fig. 11: Resonance signal from the Cs atomic fountain.

The relative effect of many random and systematic errors in atomic clocks can be reduced by using a higher clock frequency. We have examined [31] a transition in metastable Xe as a possibility for such a clock transition. Metastable xenon (Xe^*) can be laser cooled in much the same way as ground state Cs. That is, there is an

allowed transition whose excited state decays back to the original metastable state, with the metastable state being long-lived enough that it can be treated effectively as a ground state. In addition, there is a narrow, two-photon transition from the lower metastable state to a different excited metastable state that can serve as the clock transition. The transition scheme is shown in Fig. 12. The

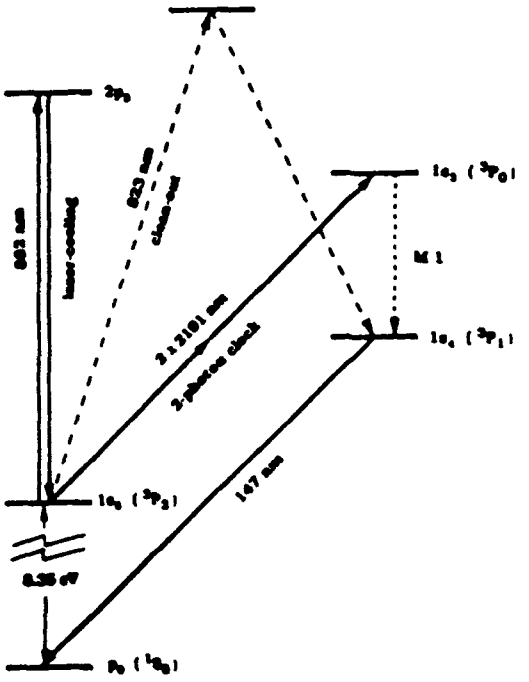

Fig. 12: Cooling and clock transitions in Xe. Some additional transitions useful for detection are also shown.*

clock transition is at 2.19 μm for each of the two photons, a wavelength that can be obtained with high stability by non degenerate parametric down conversion from a monolithic YAG laser. We are communicating with the group of Bob Byer at Stanford on the production of such radiation suitable for driving the clock transition.

The apparatus for producing and cooling Xe* is being constructed and is nearly completed. Most of the vacuum apparatus, the source and the pumps are in place, and the magnet for Zeeman-tuned deceleration of the atomic beam is being designed. We hope this beam will soon be operational.

VACUUM ULTRAVIOLET GENERATION

Laser cooling of atomic hydrogen on the resonance transition requires the generation of narrowband radiation at the Ly-α wavelength of 121.6 μm. One interest in laser cooling of hydrogen is as an alternative to cooling with a dilution refrigerator in a container whose walls are coated with liquid He. Such cold hydrogen could be used to load a magnetic or other trap for studies of quantum collective behavior or as a sample for high resolution spectroscopy, such as the measurement of the 1s-2s interval. Another interesting application of such short wavelength light is the high resolution, 2-photon spectroscopy of the 1s-2s transition in He at 120.3 μm. An absolute determination of the energy difference between the $1s^2$ ground state and the 1s2s first excited state, together with existing precision measurements of higher excited states allows a measurement of the ground state Lamb shift. The last measurement of this Lamb shift was in 1957 with conventional grating spectrometer techniques. Although the ground state Lamb shift is by far the largest quantum electrodynamic shift in He, it is also the least well known. A new laser-based measurement will test the calculation of electron correlation effects in 2-electron quantum electrodynamics.

We are carrying out experiments on VUV generation in collaboration with T. Lucatorto of NIST and T. McIlrath of NIST and the University of Maryland. Our scheme for production of VUV light is based on resonantly-enhanced sum-difference four-wave mixing in a gas, such as Kr or Xe. The general scheme uses two UV photons (around 215 nm) minus one IR photon (850-1000 nm), with the resulting 4th wave being a VUV photon (120-122 nm). The two UV photons are nearly resonant (10-100 cm^{-1}) with an excited state in the mixing gas. Phase matching is achieved by using a gas mixture composed of two gases with opposite dispersions around the frequency of interest.

Using a broadband (5-10 GHz) pulsed dye laser we have investigated VUV production with such schemes. We generate the UV photons by quadrupling the pulsed dye laser (30 mJ) operating with IR dyes. We have generated approximately 10 nJ of VUV light, both at 121 nm (Ly-α) and at 120 nm (He 2-photon), using slightly

different laser wavelengths and different excited states for the enhancement. We investigated phase-matching in the gas, and find agreement with calculations. This system is based on a 10 Hz Nd:Yag pump laser, and produces a pulsed output a few ns long. Although the power levels are adequate for both hydrogen and helium, the pulsed dye laser is not capable of producing a small enough bandwidth necessary for either the laser cooling experiments or the high resolution spectroscopy.

More recently we have built a pulsed Titanium:sapphire laser. It is an unstable resonator configuration with a graded reflectivity output coupler to produce a good spatial mode. We have demonstrated injection seeding with a single longitudinal mode diode laser. With this seed laser we will have a transform-limited source of IR for the nonlinear generation.

We are proceeding with the rest of the frequency mixing chain to produce narrowband Ly-α and narrowband light for the He two-photon transition. We will re-investigate the VUV generation with the narrow-band source, and evaluate linewidth and frequency chirps. Frequency chirps are a well known source of broadening and shifts in pulsed systems, occurring as the optical properties of the materials used for generation and mixing change during the rapid, intense pulses. We have started construction of an apparatus for the Doppler-free two-photon He measurement using photo-ionization detection of the He excitation. The wavelength metrology will be done in collaboration with C. Sansonetti of NIST, who has previously made the best measurements of many of the higher lying levels in Helium.

COLLISIONS OF LASER COOLED ATOMS

We have studied the associative ionization collisions of laser cooled atoms. In such a collision, at least as normally viewed at higher temperatures, two optically excited Na atoms combine to form $Na_2^+ + e^-$. The ionization cannot proceed without molecule formation because the two excited atoms lack sufficient energy to eject a single electron. This reaction is appealing because the ions are easy to detect and no other process produces ions, so one measures a very specific reaction. Previously [17], we have measured the collision rate for laser cooled atoms, below 1 mK, and just before the beginning of this contract period we had observed an interesting form of laser control of the reaction.

Our colleague Paul Julienne had predicted that the rate of associative ionization would be dramatically reduced when the laser intensity was low (or moderate) compared to when the intensity was high. This, in spite of the fact that the fraction of atoms in the excited state was not much different for the two conditions. Our experimental procedure turned out to be ideal for testing this prediction because we needed to switch between the high intensity, detuned trap laser and the low intensity, near resonant cooling laser field. The results obtained shortly before this contract period began confirmed the prediction qualitatively, but did not produce a good measurement of the ratio of the high intensity to low intensity rate. The initial prediction was that the high-intensity and low-intensity ionization rates should be in the ratio of about 10^4. The experiments, however, gave a ratio consistent with no ionization during the low intensity phase, but with a large uncertainty. During this contract period we have refined those initial measurements and reported [32] more definitive measurements of the ratio.

In contrast to the initial predictions, we measured ratios, depending on parameters of the molasses and trap lasers, in the range of 20 to 200, with most data falling in the range of 40 to 100. An example of the kind of data obtained is shown in Fig. 12. Simultaneous measurements of the fluorescence and the ion production rate as the trap was being switched on and off provided the required information.

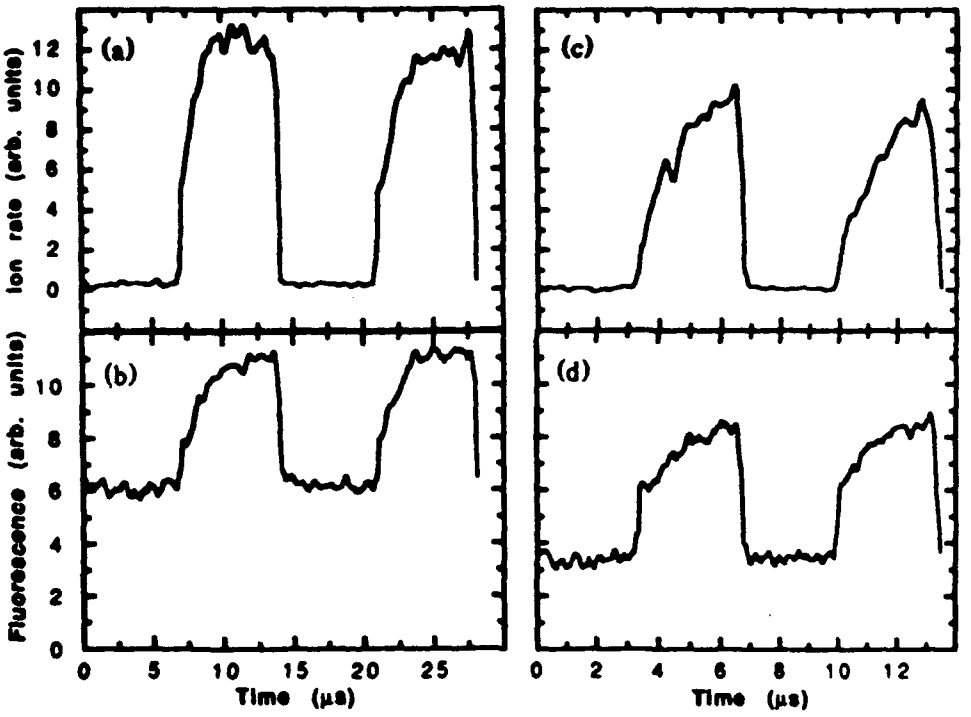

Fig. 12 (From ref.[29]): Fluorescence and ionization rates vs. time .

Perhaps even more significant than the fact that the ratio was much lower than predicted was the fact that the ionization rate remained high even when the trap was detuned several GHz from resonance. This was surprising in light of the original theory because the original idea was that associative ionization resulted from two excited atoms starting at large separation and colliding to form a molecule. At large detuning the population of the field dressed molecular level which is asymptotically a doubly excited pair of atoms becomes extremely small. This implied that the excited-excited picture of the collision was not correct.

In fact, the theory was also undergoing a significant change (see below in the supplementary program section for more details) and the new view was that the quasi-molecule was being excited in stepwise fashion as the collision progressed, passing through molecular levels. That this was happening was strongly suggested by the spectrum of ion production as a function of trap detuning shown in Fig. 13. The existence of clear resonant structure in the ionization spectrum implied the existence of intermediate resonances on the path to ionization, and the new theory confirmed the general nature of the ionization spectrum.

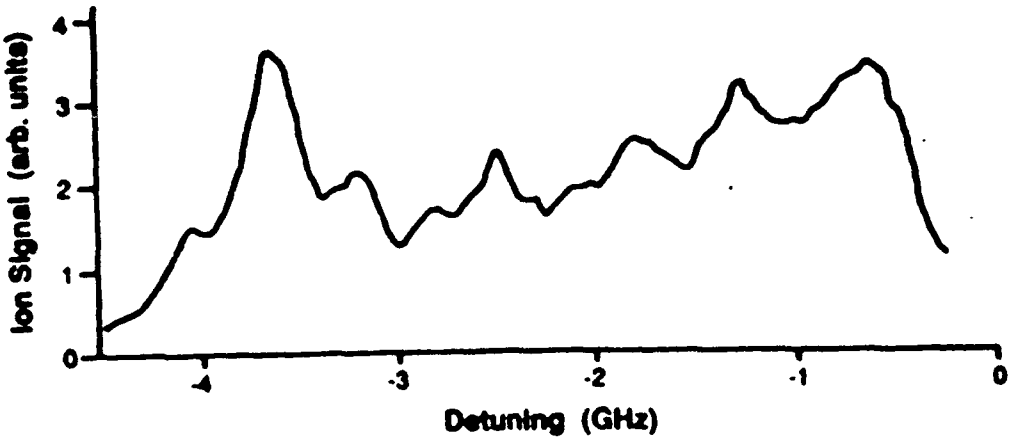

Fig. 13. The spectrum of ionization rate vs. detuning of the trap laser frequency from resonance. (From ref. [32]).

One additional remarkable observation points to still more experiments. We have seen than when the trap laser accidentally operates in two modes so that about 10% of the trap light is detuned by an additional 10 GHz to the red, the ionization rate increases by about an order of magnitude. This is presumably due to exciting a very strong intermediate resonance and implies that there is a rich resonant structure to be probed by superimposing a separately tunable laser on the trap laser. Unfortunately, we cannot tune the trap laser so far as 10 GHz off resonance without losing the trapping effectiveness. The separate laser should allow us to explore the region where we expect to see additional strong resonances.

SUPPLEMENTAL COLLISIONS PROGRAM: THEORY

The new experimental techniques for optical manipulation of atomic velocity offer the prospects of studying atomic collisions in completely new regimes of collision physics. It is critical to explore these new areas of opportunity, not only because of their fundamental interest but also because collisions can adversely affect potential applications of cooled and trapped atoms, e.g., ejecting atoms from traps or inducing pressure shifts in clocks. We have therefore taken the leadership in developing a very productive theoretical program to investigate ultracold atomic collisions. This program has relied heavily on numerous national and international collaborations.

Ultracold collisions are completely different depending on whether they occur in the presence or absence of cooling lasers. Collisions in the absence of light can be described by the well established wave function methods of scattering theory. These collisions can often occur in the Wigner law limit for laser cooled species, where only s-waves contribute to the cross sections. If the interatomic potentials and spin-dependent interactions are known, the cross sections can readily be calculated by standard techniques. Although actual cross sections are extremely sensitive to small details of the potentials and interactions, we have shown how the generalized form of the multichannel quantum defect theory can be used to get qualitative insights into the onset of such Wigner law behavior and to estimate the order of magnitude of inelastic reaction rates in the $T \rightarrow 0$ limit. We have examined ground state hyperfine changing collisions and ionizing collisions of metastable rare gas atoms. These results are summarized in a review article for Advances in Atomic, Molecular, and Optical Physics [33].

Completely new methods are required to describe excited state collisions, which occur when a cooling or trapping laser is on. This is because the collision "duration" can be many natural lifetimes, due to the extremely long range nature of the excited state resonant dipole interaction and the very slow relative velocities of the atoms. The atoms almost act as if they were quasistatically distributed and optically pumped by the laser and then drawn into a collision by the accelerating influence of attractive excited state potentials. A fully quantum mechanical description of this process that accounts for coupling of the relative motion to the spontaneous

emission degrees of freedom still is to be developed, although we are making progress on such a formulation. We have alternatively developed semiclassical models which permit the calculation of effective rate coefficients for excited state collision processes. We have implemented several approximate schemes and have applied them to several excited state collisional processes.

One process we have thoroughly examined is the fine structure changing and radiative heating processes that eject cooled atoms from a magneto-optical trap (MOT). Our first attempt used a semiclassical quasistatic model to examine the detailed molecular mechanisms for trap loss collisions in alkali species [34]. Predictions were made for Li, Na, K, Rb, and Cs traps, and good agreement was found with measurements on a Cs MOT. We found that retardation corrections to the molecular lifetimes were crucial for calculating the rates of Na and K trap loss. We have extended the semiclassical methods once more by developing a new optical Bloch equation (OBE) treatment of atomic collisions [35]. The OBE method treats the case of saturation of the cooling transition. Although the OBE method is semiclassical in the sense that it uses semiclassical localization within the framework of the WKB approximation for generating the OBE's, the method actually gives answers that are completely independent of the choice of a reference trajectory for integrating the equations. The primary approximation in the method relates to how energy conservation criteria are applied to choosing the excited state WKB wave function in the case of dissipation by spontaneous emission. Questions relating to this issue can not be answered within the framework of our semiclassical OBE theory. We have therefore used an alternative quantum approach based on a different WKB treatment of the weak field limit to justify the way we apply energy conservation criteria in the semiclassical OBE formulation [36]. We have carried out new calculations of the fine structure changing probabilities in Cs and Rb [37], and applied the OBE method to predict new trap loss rates. The calculated rates are in reasonable agreement with measurements on Na, Rb, and Cs MOTs, but there are still important differences in detail that need to be understood before we can have real confidence in the ability of theory to be quantitative.

The process of associative ionization in a Na trap is a process which we have previously studied theoretically and experimentally [38, 39]. New experiments (see the section on collisions of laser cooled atoms, above) verified the prediction that the effective rate

coefficient for this process should be much smaller in the molasses phase of the NIST hybrid trap than during the trapping phase [39]. We have now carried out detailed calculations that attempt to provide detailed molecular mechanisms and predictions concerning this reaction [40, 41]. We now view the process as one of photoassociative ionization in which the doubly excited state which ionizes is produced at long range by a two step molecular process which operates in a fundamentally different way during the trapping and molasses phases of the hybrid trap. In the trapping phase, the laser detuning and Rabi frequency are many times the natural linewidth of the atomic transition. Molecular bound state resonance structure, strongly perturbed by the intense laser field, modulates the photoassociative ionization signal [40]. This process can be fully described by a conservative Hamiltonian, unaffected by excited state decay. In the molasses phase, the detuning and Rabi frequency are on the order of the natural linewidth. Since the molecule can only be excited when the atoms are very far apart, the excited state has a high probability of decaying by spontaneous emission before the atoms move close enough together to form a molecular ion. We have used the semiclassical OBE treatment of this process and find the right order of magnitude for the effective rate coefficient if the role of hyperfine structure in the excited state is taken into account [41].

The theoretical studies to date have laid the foundation for understanding the basic physics which occur in ultracold atomic collisions. There are still many aspects of this problem that have not yet been correctly treated and many fundamental questions that remain unanswered. There is still a strong need for experimental verification (or falsification) of theoretical predictions, as well as a need to develop the experimental phenomenology of ultracold collisions, including the connection between ultracold and normal temperatures. Theory predicts that excited state collisions are subject to manipulation by varying the detuning and intensity of one or more external fields. One aspect of this is the "catalysis laser" concept of Sesko et al. [42]. We have calculations in progress that show how a weak blue detuned laser should be able to turn off or on the photoassociative ionization signal. We also have calculation in progress showing that the effective rate coefficient of Penning ionization of trapped He metastable atoms can be varied by two orders of magnitude by turning the light on or off, a result consistent with recent measurements by the Paris group. The predicted role of retardation corrections in determining trap loss

rates in Na and K MOTs has not yet been verified experimentally. Recent experiments point to the likely role of excited state hyperfine structure in trap loss collisions, an effect not yet accounted for in the theories. Recent calculations by Verhaar and colleagues suggest that collisional processes may be favorable for achieving Bose-Einstein condensation of laser cooled Cs. These calculations do not take into account the likely role of second-order spin-orbit contributions to the ground state effective spin-spin interaction in the Cs_2 molecule. We estimate that such terms in the Hamiltonian may cause orders of magnitude changes in certain collision rates.

SUPPLEMENTAL COLLISIONS PROGRAM: EXPERIMENT

The program in cold collisions at the University of Maryland has centered on the development of techniques for studying cold and ultra cold collisions in atomic beams where the energy dependence and polarization dependence of collisions are more accessible than in the cell-type experiments conducted in atom traps. These experiments complement the laser trap collision experiments which achieve lower temperatures, but without the wide range of possible collision energies.

In the past year we have developed a robust travelling wave optical buildup cavity from which we extract up to 500 μW watts of 285 nm light through a temperature -tuned frequency-doubling ADA crystal. The UV beam selects a velocity group from the Na(3s $2S1_{/2}$) → Na(5p 2P) transition with a sodium atomic beam. We have measured and reported the first results from these experiments--associative ionization rate constants at 18 mK collision energy --as a function of polarization and optical field intensity. The ability to independently vary polarization, intensity, and frequency of the collision -inducing light field distinguished atomic beam experiments from optical trap experiments.

The dynamics of associative ionization (AI) between excited Na atoms,

$$Na(3p\ ^2P_{3/2}) + Na(3p\ ^2P_{3/2}) \rightarrow Na_2^+ + e^-$$

continues to be a convenient test case for theory and experiment of inelastic processes in radiation fields. We began a series of atomic beam experiments [43] measuring the probability of AI as a function of velocity and polarization, under "conventional" collision conditions, as a prelude to entering the ultracold regime. We soon realized that velocity group selection would be a fruitful technique for examining new collision physics when the collision time becomes long compared to the characteristic time of radiative dissipation. By exploiting the low *relative* velocity of collision *within and between* narrow velocity groups we were able to measure the excitation function and polarization dependence of AI from 1000 K to about 65 mK [44,45]., which is just at the threshold of the ultracold regime. The relative velocity of collisions within a velocity group is limited by the width of the group itself. The

absence of power broadening the radiative lifetime of the excited state determines this width. Collision energies in the ultracold regime dictate the selection of a velocity group narrower than that obtainable from the Na (3s → 3p) transition. The Na (3s → 5p) transition appeared to be a likely candidate because frequency doubling 570 nm light, available from a ring dye laser, generated the resonant frequency at 285 nm. The natural width of the Na (3s → 5p) transition, less than 1 MHz, is over one order of magnitude narrower than the Na (3s → 3p) transition, and effectively lowers collision energy to a few millikelvin. Frequency doubling cw lasers, however, is nontrivial and required constructing an optical buildup cavity and the regulation of an ADA crystal to a stability of 10 mK. We committed last year's resources of time and money to developing a reliable, sufficiently intense source of UV light and to acquiring the necessary acousto-optic modulators so as to begin to carry our ultra-narrow velocity group experiments. This effort has recently yielded the first results on the polarization and intensity dependence of Al at 18 mK and was reported at the Cold Collisions workshop in April [46]. We will submit a Phys. Rev. Lett. on these results before the end of July.

Concurrent with the Al experiments we have also been pursuing the theory of fine-structure changing collisions in the heavy alkalis, RB and Cs:

$$Rb(5s\ ^2S_{1/2}) + Rb\ (5p\ ^2P_{3/2}) \rightarrow Rb(5s\ ^2S_{1/2}) + Rb(5p\ ^2P_{1/2})\ .$$

Olivier Dulieu from the Laboratoire des Collision Atomiques et Moleculaires in Orsay, France has been working with Weiner and Julienne, using his fully quantal close-coupling codes to investigate the sensitivity of theoretical results to small changes in the form of molecular potentials, the strength and form of the spin-orbit matrix elements, and the possibility of a quantal mass isotope effect. These studies have been inspired by the importance of fine structure changing collisions to optical trap loss rates, recent measurements of which have been reported [46] with significant departures from the predictions of Julienne and Vigue. We have reason to believe that a surprising isotope effect in the observed Rb trap loss rate may be due to the mass difference between ^{85}Rb and ^{87}Rb, but reliable results await more precise potential parameters before publication.

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